Observations of Intrahour Variable Quasars: Scattering in our Galactic Neighbourhood[1]

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ABSTRACT

Interstellar scintillation (ISS) has been established as the cause of the random variations seen at centimetre wavelengths in many compact radio sources on timescales of a day or less. Observations of ISS can be used to probe structure both in the ionized insterstellar medium of the Galaxy, and in the extragalactic sources themselves, down to μas scales. A few quasars have been found to show large amplitude scintillations on unusually rapid, intrahour timescales. This has been shown to be due to weak scattering in very local Galactic "screens", within a few tens of parsec of the Sun. The short variability timescales allow detailed study of the scintillation properties in relatively short observing periods with compact interferometric arrays. The three best-studied "intrahour variable" quasars, PKS 0405−385, J1819+3845 and PKS 1257−326, have been instrumental in establishing ISS as the principal cause of intraday variability at centimetre wavelengths. Here we review the relevant results from observations of these three sources.

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1. Introduction

Intraday variability (IDV) was discovered at centimetre wavelengths in the mid-1980s (Witzel et al. 1986; Heeschen et al. 1987). For over a decade there was much debate over whether the variability could be source-intrinsic, or whether it was caused by extrinsic mechanisms, namely gravitational microlensing or interstellar scintillation (ISS). Intrinsic explanations imply very high brightness temperatures, requiring Doppler factors of 50–200 for consistency with the Inverse Compton limited brightness temperature of $\sim 10^{12}$ K. Over the last decade much observational evidence has accumulated to support ISS as the principal mechanism for centimetre wavelength IDV.

The largest survey for IDV to date is the MASIV 5 GHz VLA Survey of more than 500 compact, flat-spectrum radio sources (Lovell et al. 2003). The MASIV Survey revealed variability on timescales of up to 3 days (the duration of the MASIV observing sessions) with typical modulation indices $\sim 1 - 10\%$, in more than half of the observed sources during one or more epochs. Among other factors, the Galactic latitude distribution of the scintillating sources provides strong evidence of an interstellar origin of the observed variability. While ISS of flat-spectrum radio sources is common, variability on timescales of a few hours or less and with rms amplitude modulation more than $\sim 10\%$ is extremely rare. At the extreme end of the IDV spectrum, three quasars are known to show large variations on timescales of less than 1 hour. These are PKS 0405−385 (Kedziora-Chudczer et al. 1997), J1819+3845 (Dennett-Thorpe & de Bruyn 2000) and PKS 1257−326 (Bignall et al. 2003). Because of the short timescales of the fluctuations, they can be well sampled in a typical 12 hour observing session with an interferometer such as the Australia Telescope Compact Array (ATCA) or Westerbork Synthesis Radio Telescope (WSRT), and this has enabled detailed studies of the variability characteristics. As described by Macquart & Jauncey (2002), ISS can be used to probe both the radio structure of the high-brightness source components and the insterstellar medium (ISM) responsible for the rapid variations. In this paper we review the discovery, observations and analysis of the three well-studied intrahour variable (IHV) sources.

2. The Intrahour Variable Quasars

2.1. PKS 0405−385

The discovery of hourly variations in the southern $z = 1.285$ quasar PKS 0405−385 at 4.8 and 8.6 GHz caused serious difficulties to explain the variability as intrinsic to the source (Kedziora-Chudczer et al. 1997). As shown in Fig. 1, the variability was so large and rapid, with changes of up to 50%, or ~ 1 Jy, in an hour or less at 5 GHz, that the implied

brightness temperature for intrinsic variability was in excess of 10^{21} K and so the authors were led to consider ISS. The observed frequency dependence of the modulation amplitude and timescales were both consistent with weak scattering at frequencies of 5 GHz and above, and strong scattering at frequencies below 5 GHz, with the largest amplitude variations close to the transition frequency (Walker 1998). Remarkably, the dramatic variations ceased after a few months.

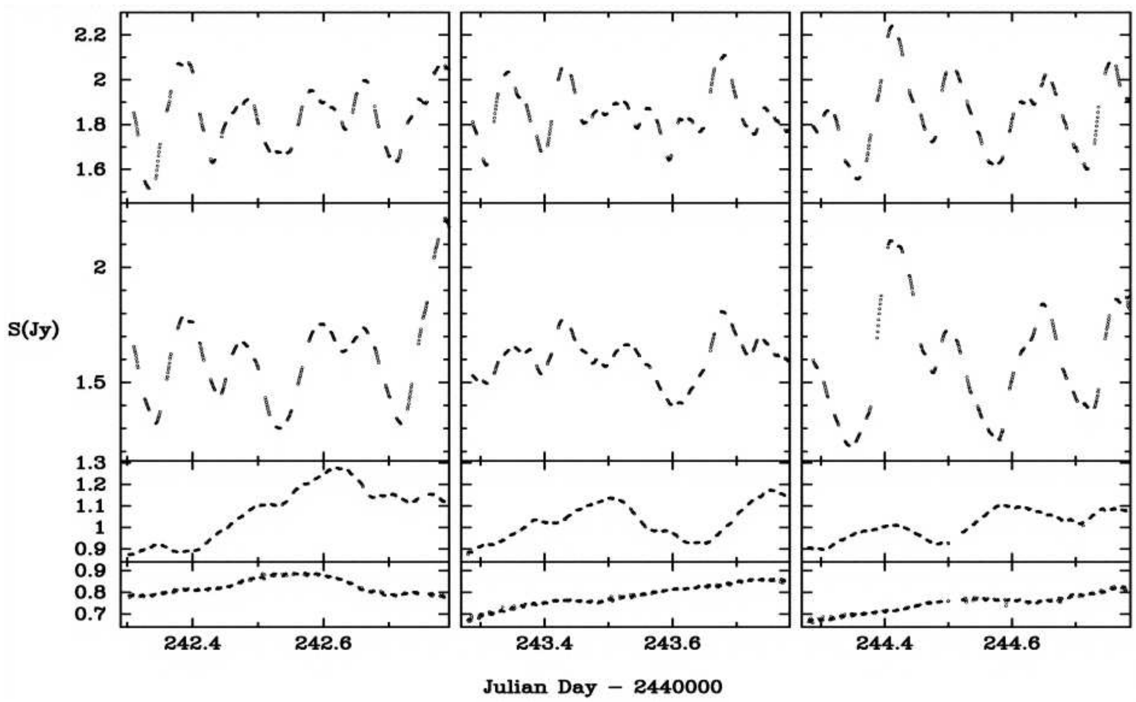

Fig. 1.— Rapid variations observed in PKS 0405−385 over three days in June 1996, from Kedziora-Chudczer et al. (1997). The observed frequencies are, from top to bottom, 8.6, 4.8, 2.4 and 1.4 GHz.

Confirming evidence for an ISS origin of the rapid variability in PKS 0405−385 came with the next episode of IDV in late 1998. The variations were sufficiently rapid and strong that it was feasible to time the variability patterns at two widely spaced telescopes and search for any time delay between the patterns. Such an experiment can only be done if the variability timescale is sufficiently short, typically an hour or less, and the measurement accuracy high enough to detect flux density changes in tens of seconds, as was the case with PKS 0405−385. A successful experiment was undertaken between the ATCA and the Very Large Array (VLA) at 4.8 and 8.6 GHz. At the southerly declination of $-39°$ the geometry is less than ideal, with very little overlap between PKS 0405−385 rising at the ATCA and setting at the VLA, but nevertheless a significant time delay of 140 ± 25 seconds

was found, with the pattern arriving first at the VLA (Jauncey et al. 2000). Such a time delay demonstrates unequivocally that ISS is the mechanism responsible for the dramatic variability in this source, at the same time ruling out intrinsic variability. The time delay also constrains the velocity at which the scintillation pattern drifts across the baseline.

Unfortunately once again the rapid variability in PKS 0405−385 ceased before the measurements could be repeated, and did not reappear again during the course of an ATCA monitoring program which lasted until mid-2002. In 2004, however, PKS 0405−385 was once again found to be showing large and rapid variations (Cimo et al. 2004). ATCA observations in early 2006 revealed extremely rapid fluctuations on timescales much less than 1 hour, allowing the pattern time delay between the VLA and the ATCA to be measured again, this time to very high accuracy, 177.2±4.5 seconds (Kedziora-Chudczer, presented at "Challenges of Relativistic Jets" meeting in Cracow, Poland, June 2006).

Like many other IDV sources, PKS 0405−385 shows more rapid and larger fractional variations in polarization than in total intensity, which can be interpreted as being due to two or more differently polarized, scintillating sub-components within the total intensity scintillating component. A detailed correlation analysis of the Stokes I, Q, and U fluctuations of PKS 0405−385 observed in 1996 was performed by Rickett et al. (2002). It was shown that the observed fluctuations were consistent with a local enhancement in scattering at a distance in the range of 3–70 pc from the Earth (taking into account uncertainty in the scintillation velocity), which is much closer than the screen distance assumed by Kedziora-Chudczer et al. (1997). The favoured model of Rickett et al. placed the screen at a distance of about 25 pc. The observations at 8.6 GHz are then well modelled by scintillation of a $30 \times 22\,\mu$as source, with about 180° rotation of the polarization angle along its long dimension as illustrated in Fig. 2, from Rickett et al. (2002). At least 3 differently polarized components are required to fit the observations and the resulting model is not uniquely constrained. For the model which is illustrated, the authors chose to minimise the implied source brightness temperature, and allowed a maximum of 70% fractional polarization, which is close to the theoretical maximum from a uniform synchrotron source. The model peak brightness temperature is 2×10^{13} K, lower than that inferred in the 1997 paper because of the reduced distance to the scattering screen.

2.2. J1819+3845

After PKS 0405−385, the next IHV quasar to be discovered was the fainter quasar J1819+3845, for which the variability was discovered serendipitously with the WSRT (Dennett-Thorpe & d 2000). With variations of up to 10% per minute at 5 GHz, J1819+3845 exhibits the most

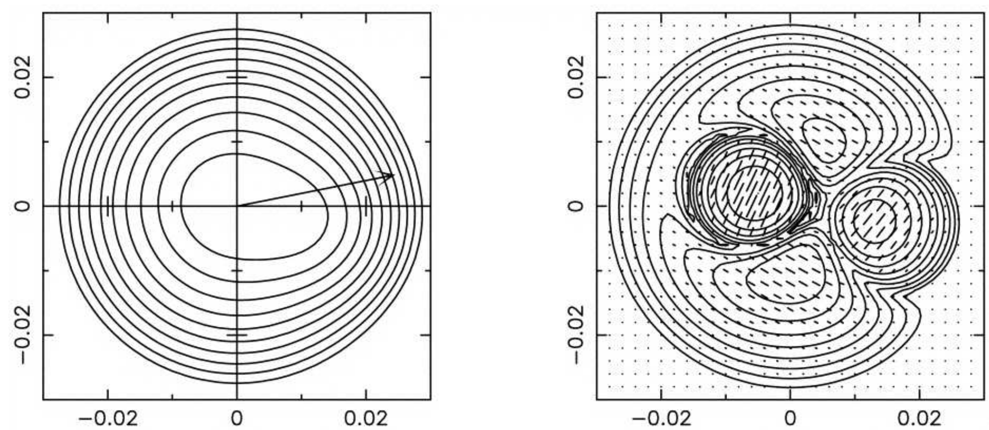

Fig. 2.— A model for the μas-scale polarized structure of PKS 0405−385, from Rickett et al. (2002). The angular scale is shown in milliarcseconds. The left-hand panel is the total brightness temperature with the peak at about 2×10^{13} K, with the arrow indicating the scintillation velocity direction. The right-hand panel is the polarized brightness with maximum 70% of the total brightness.

dramatic radio variability observed in an extragalactic source. If such variations were intrinsic then the source, at $z = 0.54$, would have an angular size of order 10 nano-arcseconds and would therefore *have* to scintillate, such that ISS would in any case dominate the observed variability. Unlike PKS 0405−385, J1819+3845 does not exhibit outbursts of variability but rather has continued to show its characteristic rapid variability since discovery. The rapidity of the variability in J1819+3845 was immediately explained as being due to an unusually nearby scattering screen, within a few tens of pc from the Sun (Dennett-Thorpe & de Bruyn 2000).

The discovery of a changing time delay of up to $\sim$ 100 seconds between the VLA and WSRT (Dennett-Thorpe & de Bruyn 2002), and of a dramatic annual cycle in the characteristic timescale, $T_{\rm char}$, of its variations (Dennett-Thorpe & de Bruyn 2003), left no doubt that the principal mechanism responsible for the dramatic variability of J1819+3845 is also ISS. The annual cycle results from the change in scintillation velocity due to the Earth's orbital motion, and depends on both the transverse velocity of the scattering plasma and the two-dimensional structure of the scintillation pattern. An analysis of the J1819+3845 annual cycle from more than two years' of monitoring with WSRT reveals a highly anisotropic scintillation pattern with an axial ratio > 6:1 (Dennett-Thorpe & de Bruyn 2003). Fig. 3 shows $T_{\rm char}$ measurements over two years for J1819+3845, overlaid with the model annual cycle for the best fit screen velocity and anisotropic pattern. From the scintillation characteristics the

scattering plasma is found to reside in a strong, thin scatterer within ~ 10 parsecs, which leads to a source size at 5 GHz of 100 to 900 μas and brightness temperature of 10^{10} to 10^{12} K.

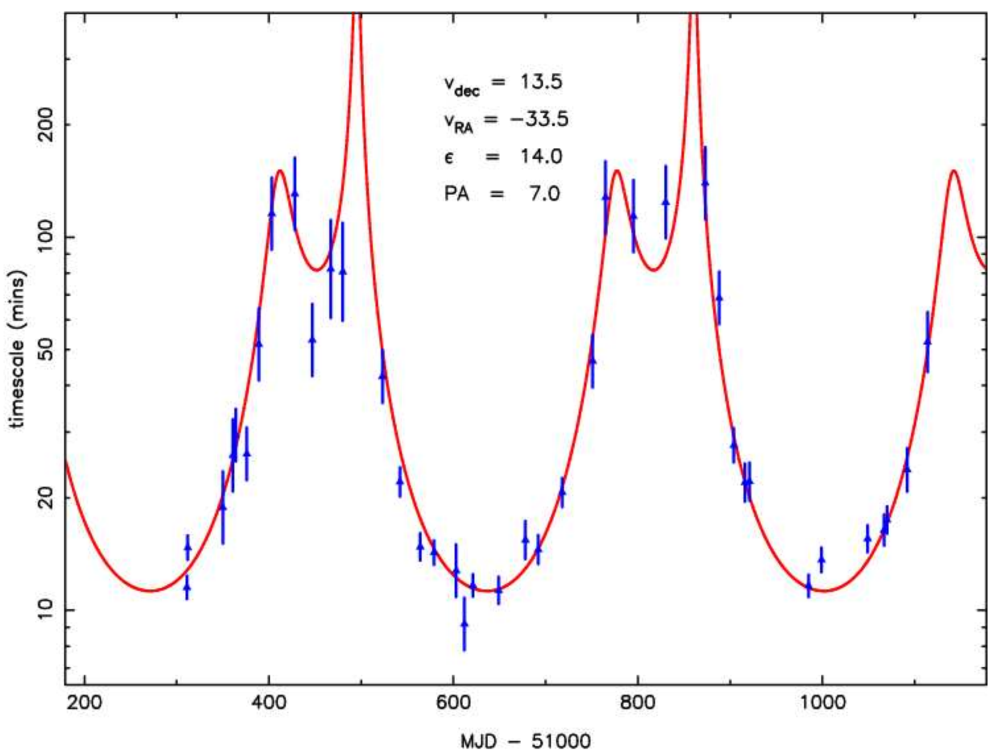

Fig. 3.— The large annual modulation in characteristic timescale observed in J1819+3845 – note that the y-axis is shown on a logarithmic scale. The line shows the best fit to these measurements and two-station time delay data, fitting for the screen velocity and an elongated scintillation pattern (from Dennett-Thorpe & de Bruyn 2003).

While the brightness temperature inferred from the annual cycle of J1819+3845 is not especially high, there is some evidence for very high-brightness components in the source from an analysis of the variations at 1.4 GHz. Macquart & de Bruyn (2006) reported the discovery of rapid, frequency dependent variations which could be modelled as diffractive interstellar scintillation (DISS). This is the only reported case of DISS of a quasar. If the interpretation of Macquart & de Bruyn is correct, the implied brightness temperature is in excess of 2×10^{14} K. If the brightness temperature is indeed this high, then special emission processes may be present, e.g. cyclotron maser emission (Begelman et al. 2005).

2.3. PKS 1257−326

The IHV quasar PKS 1257−326 was discovered serendipitously with the ATCA (Bignall et al. 2003). ATCA monitoring of PKS 1257−326 at 4.8 and 8.6 GHz revealed an annual cycle in the timescale of variability which is repeated over several years of observations at both frequencies. Successful time delay measurements have been made for PKS 1257−326 between the ATCA and VLA on three occasions during 2002-03 (Bignall et al. 2006). The observed annual cycle and time delays demonstrate conclusively that the rapid, large-amplitude variability of PKS 1257−326 is entirely due to ISS. A striking feature of the time delay measurements for PKS 1257−326 is the length of the delays; for both PKS 0405−385 and J1819+3845 the measured delays were $\sim 2-3$ minutes at most, whereas for PKS 1257−326 delays as long as 8 minutes were observed, as shown in Fig. 4. These long time delays, when combined with the annual cycle in variability timescale, imply that the scintillation pattern must be highly anisotropic, as has also been determined for the other two fast scintillators (Rickett et al. 2002; Dennett-Thorpe & de Bruyn 2003).

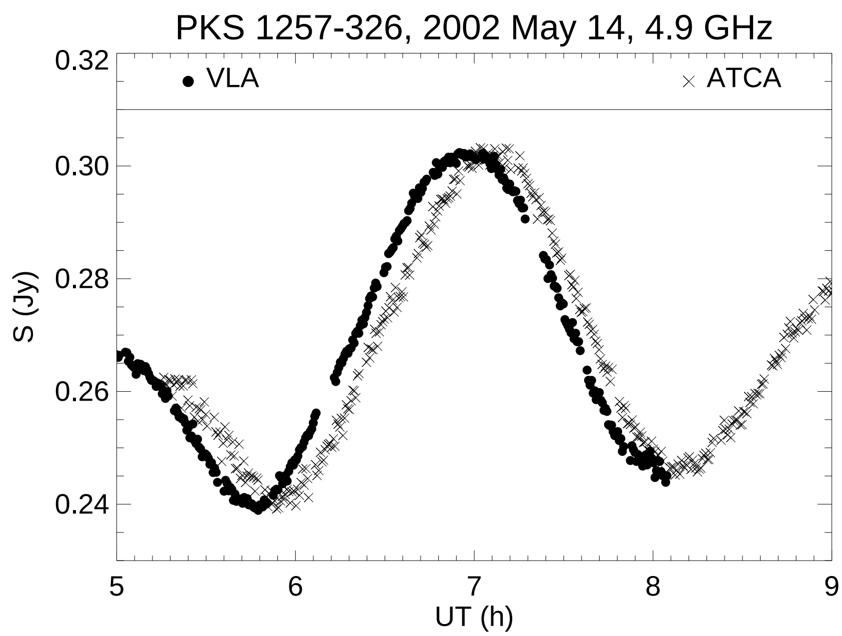

Fig. 4.— Simultaneous observations of PKS 1257−326 with the VLA and ATCA from 2002 May, showing a clear time delay of 8 minutes between the variability patterns with the VLA leading.

In principle the annual cycle and time delay observations can be combined to determine the peculiar velocity of the scattering medium as well as properties of the scintillation pattern,

i.e. its characteristic length scale as well as the axial ratio and position angle of anisotropy in the pattern. However there are degenerate solutions when the scintillation pattern is highly anisotropic, as shown in Bignall et al. (2006). The characteristic scale of the scintillation pattern along its short axis can still be uniquely determined, however the pattern scale and component of scintillation velocity parallel to the long axis are degenerate.

Interestingly, PKS 1257−326 also showed an annual cycle in the time offset between the 4.8 and 8.6 GHz scintillation patterns observed over the course of 2001 (Bignall et al. 2003). This was modelled as a jet-like source which is optically thick between 5 and 8 GHz. That the time offset always has the same sign implies that the scattering screen always crosses the 8.6 GHz "component" first, thereby constraining the direction of the offset. For a screen distance of 10 pc (Bignall et al. 2006), the fitted displacement vector corresponds to an offset of approximately 12 μas which at the source redshift of $z = 1.26$ corresponds to a projected linear displacement of order 0.1 pc. More recent monitoring data suggests the offset has changed, perhaps as a result of the intrinsic evolution of the source. Both the flux density and spectral index of the source have slowly evolved over several years of ATCA monitoring.

3. Discussion

In weak scattering, the characteristic length scale of the scintillation pattern is related to the size of the first Fresnel zone, $r_{\rm F} = \sqrt{cL/(2\pi\nu)}$, where ν is the observing frequency and L is the distance to the scattering medium which is assumed to be confined to a plane. Thus for a given velocity of the scattering screen, a shorter scintillation timescale, $T_{\rm char}$, implies a closer scattering screen. When the source has angular size larger than the Fresnel scale at the screen, however, then $T_{\rm char}$ is increased and the amplitude modulation is reduced. The closer the scattering screen, the larger the angular size of the source which can scintillate through it. This implies that for AGN, whose angular sizes are generally inferred to be larger than the Fresnel scale at distances greater than a few tens of parsec, large and rapid amplitude scintillation may *only* be observed through nearby scattering screens. The fact that only a handful of IHV quasars has been found suggests that the covering fraction of nearby scattering material in the Galaxy is very small. Another consideration is that more distant scattering material can cause angular broadening which may quench the scintillation in foreground screens.

Both source and screen properties play a role in the observed scintillation of AGN. Of the three IHV quasars discussed here, two show long-lived rapid scintillation over several years of monitoring, while PKS 0405−385 shows episodes of IHV, lasting from months to years. The analysis of Kedziora-Chudczer (2006) found no clear connection between long-

term source-intrinsic changes and episodes of IHV. This suggests that intermittency in ISM turbulence, rather than source evolution, could be responsible for the episodic IDV observed in PKS 0405−385.

All three IHV sources show evidence for highly anisotropic scattering at frequencies of 5 GHz and above. Highly anisotropic ISM turbulence is suggested also from other observations, e.g. the parabolic arcs observed in the secondary spectra of pulsars undergoing diffractive scintillation (Walker et al. 2004). Unfortunately, high anisotropy leads to ambiguity in solving for the scintillation parameters, which to some extent limits the information on source structure obtainable from ISS observations. Nevertheless, ISS is a useful probe of source structure on scales smaller than can be resolved with current VLBI, and also of properties of turbulence in the local ISM.

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